A DTN Packet Forwarding Scheme Inspired by Thermodynamics

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Outline

- Overview of DTNs
- Packet forwarding
  - Model
- Thermodynamics – Exchange of Heat
  - Temperature
  - Description of algorithm
- Preliminary Result & Conjectures
  - Distributional convergence of temperatures
- Simulation result

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Overview of DTNs

- Evolution of Delay Tolerant Networks to Disruption Tolerant Networks
- Mobile nodes moving around an area/domain
- Sparse node connectivity
  - Network disconnected most of the time
  - Nodes rely on other nodes to relay bundles (i.e., messages) exploiting mobility
  - Mobility of nodes unknown in advance and may change over time
  - Multiple copies of bundles generated to increase the probability of successful delivery (e.g., controlled flooding)

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Packet forwarding

- No fixed routing and global routing information
  - No end-to-end paths available from sources to destinations most of the time
    - Consequence of lack of network connectivity
  - Location of destinations and sequence of nodes to traverse unknown in advance
    - Disseminating/maintaining or accessing routing information difficult and impractical
  - When two nodes come in contact, they exchange information and figure out who will forward which bundles (if any)

Packet forwarding

- For forwarding/routing of bundles ….
  - Each node must make local decisions based on local information
    - Without global information or pre-specified routing information
  - When two nodes meet, they must estimate the quality of the other node as a possible relay node
    - Metric should allow them find out who has a better chance of successfully delivering bundles, possibly through other relay nodes, to the intended destinations

Packet forwarding

- Quality of a node as a relay node for a destination depends on …
  - Set of other nodes it meets and interacts with;
  - Distribution of inter-meeting times with these nodes and that of meeting times;
  - Quality of channel when in contact
- Determined by mobility of the nodes!

Packet forwarding

- Should **learn** and **exploit** knowledge on mobility of other nodes

- Question is…. How do we do that??

- Simplicity – less chance of something going wrong!
  - Summarize with one variable
  - Node's **exposure** to the gateway(s)
    - How much information it can forward towards gateway(s)
  - Proxy to quality as a relay node

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Model for our setup

- Set of nodes – $\mathcal{N} \equiv \{1, 2, \cdots, n\}$
- Nodes move on some domain $\mathbb{D} \subset \mathbb{R}^2$
  - Mobility need not be homogeneous
- Trajectory of node ***i*** – $\mathbb{L}_i := \{\mathbf{L}_i(t); t \in \mathbb{R}_+\}$
  - $\mathbf{L}_i(t)$ - location of node i at time t
- Messages arrive at each node according to some stochastic process
  - Messages to be delivered to an information gateway or sink
  - Gateway = node n

Model – one-hop connectivity

- One-hop connectivity: For each pair of nodes i and j, given by an on-off process $\mathbb{C}_{ij} \equiv \{C_{ij}(t); t \in \mathbb{R}_+\}$ where

$$C_{ij}(t) = \begin{cases} 1 & \text{if } \left\| L_i(t) - L_j(t) \right\|_2 \leq \gamma \\ 0 & \text{otherwise} \end{cases}$$

  - Can communicate if and only if the distance is not larger than γ

Assumption

- Meeting times likely to be larger than the amount time needed to complete transfer of messages
- Transfer of bundles take place instantly
  - Nodes complete all desired transfer of messages while they are in contact
- Other case addressed using an ant-based packet forwarding scheme (another story)

Goal

- Goal: To design a simple, yet efficient single-copy packet forwarding scheme that exploits knowledge of nodes' mobility
- Introduce a time-varying measure at each node which quantifies either direct or indirect exposure to sink
  - Depends on nodes' mobility
    - Frequency of meetings and meeting times
  - Serves as an estimate of a node's ability to forward messages to sink
  - Used to guide packet forwarding decisions
    - Node with a smaller value forwards messages to node with a larger value

Desired properties of such a meaure

- Lies in a compact interval
- Increases while the node is in contact with sink
- Decreases when the node is not in contact with any other node
- While two nodes are in contact, their values are continually updated
  - Larger value decreases; smaller value increases

Temperature

- Each node maintains a variable called temperature
  - Serves as a measure of exposure to sink
  - $\theta_i(t)$ - temperature of node i at time t

- Heat exchange rule: When two nodes i and j are in contact, the rate of change in temperature at node i is given by

$$\Delta\theta_i = \lambda_{ij}(\theta_j - \theta_i) \ , \ i, j \in \mathcal{N} \ ,$$

  where $\lambda_{ij} \geq 0$ is the heat exchange coefficient from node j to node i
  - $\lambda_{ij} = \lambda_{ji}$ for all $i, j \in \mathcal{N}^\star := \mathcal{N} \setminus \{n\}$

… to a practical algorithm

- Temperature of sink is constant:

$$\theta_n = \theta_n(t) = T > 0 \text{ for all } t \geq 0$$

  - $\lambda_{ni} = 0 \text{ for all } i \in \mathcal{N}^\star$

- Virtual ground (node 0) with constant temperature:

$$\theta_0 = \theta_0(t) = 0 \text{ for all } t \geq 0$$

  - $\lambda_{0i} = 0 \text{ for all } i \in \mathcal{N}^\star$
  - All nodes in $\mathcal{N}^\star$ are in contact with the ground unless in contact with sink
    - Lose heat to ground

… to a practical algorithm

- Rate of heat exchange is additive
  - When a node is in contact with more than one other node (in addition to ground):

    rate of temperature change

    = sum of rates at which temperature would change when it were in contact with each of these nodes separately

Description of algorithm

- Temperature update rule: For all $i \in \mathcal{N}^\star$

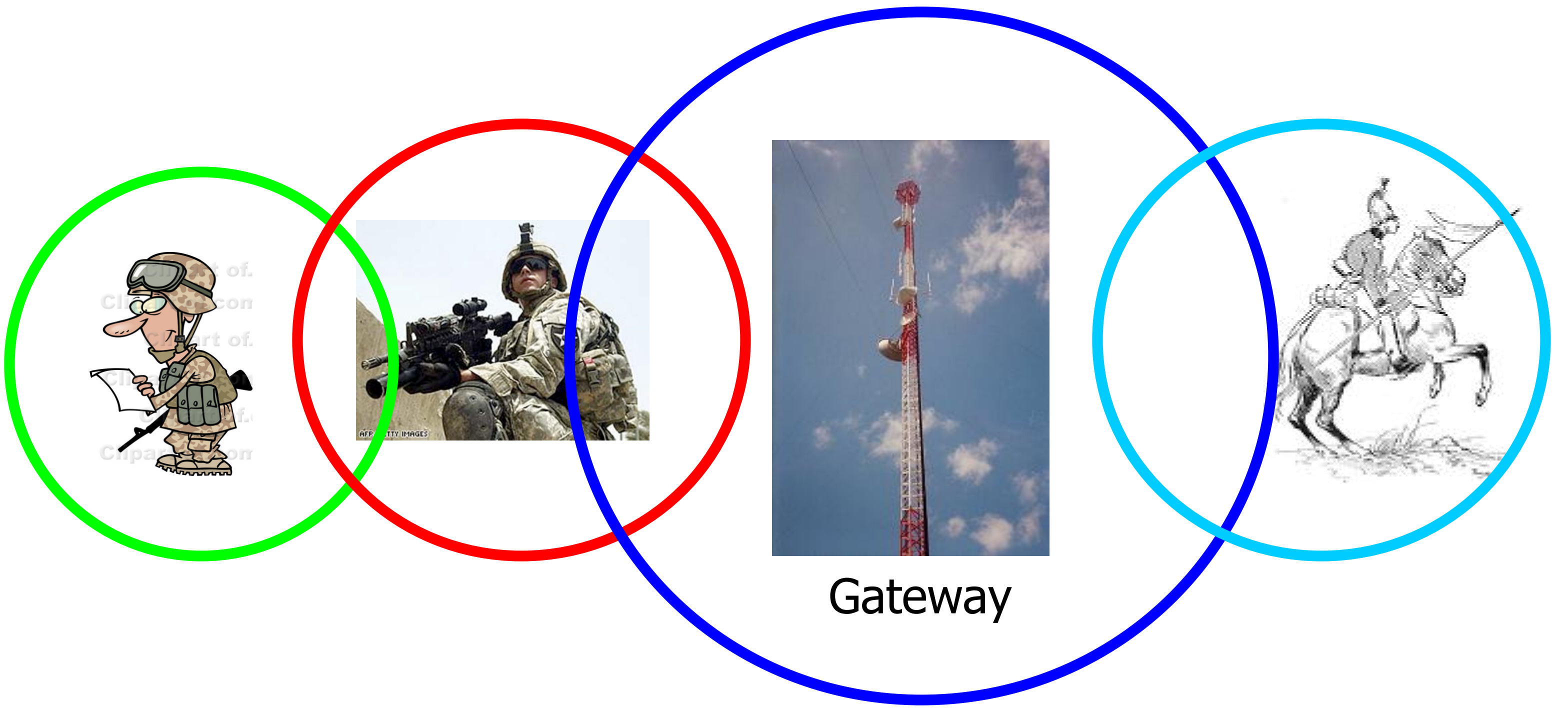
$$\frac{d}{dt}\theta_i(t) = \sum_{j=1}^{n} \lambda_{ij}(\theta_j(t) - \theta_i(t))\ 1\left\{\left\|L_i(t) - L_j(t)\right\|_2 \leq \gamma\right\} - 1\left\{\|L_i(t) - L_n(t)\|_2 > \gamma\right\}\ \lambda_{i0}\ \theta_i(t)\ , \tag{1}$$

where

$$1\{A\} = \begin{cases} 1 & \text{if event } A \text{ is true} \\ 0 & \text{otherwise} \end{cases} .$$

  - Initial conditions: $\theta_i(0) = 0$ for all $i \in \mathcal{N}^\star$
  - Temperature given by continuous-time stochastic process

Example:



Observations…

- (Roughly) same temperature of two nodes that meet often
  - Can exchange messages between them regardless of which node first takes on the messages
  - Approximately equally preferable as relay node
- When a node stays in contact with the sink for a long time
  - Temperature will asymptotically approach that of sink
  - Can deliver messages to sink on behalf of other nodes
    - Good relay node
- Similar temperature profile of nodes in group mobility model

Stability of temperature

- **Proposition:** *The temperature processes* $\Theta_i, i \in \mathcal{N}$*, produced by the differential equations in (1) are stable in the sense that, starting from any non-negative initial values* $\theta_i(0) < \infty$*,* $i \in \mathcal{N}^\star$*, the temperatures satisfy*

$$\theta_i(t) \leq \max\{T,\ \max\{\theta_i(0); i \in \mathcal{N}\}\}$$

for all $t \geq 0$ *and for all* $i \in \mathcal{N}$*. Furthermore, if we assume the initial conditions* $\theta_i(0) = 0$ *for all* $i \in \mathcal{N}^\star$*, we have* $0 \leq \theta_i(t) < T$ *for all* $t \geq 0$ *and for all* $i \in \mathcal{N}^\star$*.*

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Discrete-time model

- Discrete-time approximation
- Time is divided into contiguous timeslots t = 0, 1, …
  - Duration of timeslot = Δ
  - No change in connectivity within a timeslot
- Equation (1) is approximated as

$$\theta_i(t+1) - \theta_i(t) = \sum_{j=1}^{n} \lambda_{ij}^{D} \left(\theta_j(t) - \theta_i(t)\right) 1\left\{\left\|L_i(t) - L_j(t)\right\|_2 \leq \gamma\right\} - 1\left\{\|L_i(t) - L_n(t)\|_2 > \gamma\right\} \lambda_{i0}^{D}\, \theta_i(t)$$

  - Denote vector of temperatures by $\Theta = (\theta_i; i \in \mathcal{N})$

Discrete-time model

- **Assumption:** The trajectories $\mathbb{L} := \{\mathbb{L}_i; i \in \mathcal{N}\}$ of the nodes are ergodic and jointly stationary.
  - $\mathbb{L}_i = (L_i(t); t = 0, 1, \ldots)$
  - Implies that the one-hop connectivity process

$$\mathbb{C} \equiv \{\mathbb{C}_{ij}; i, j \in \mathcal{N} \cup \{0\}\}$$

is stationary and ergodic, where

$$\mathbb{C}_{ij} = \{C_{ij}(t); t = 0, 1, \ldots\}$$

Distributional convergence

- Suppose that the connectivity matrix

$$\mathbb{C}(t) = [C_{ij}(t); i, j \in \mathcal{N} \cup \{0\}] \ , \ t = 0, 1, \ldots$$

  is a given by a sequence of independent and identically distributed (i.i.d.) random vectors

- Assumption: A node can be in contact with at most one other node (not including ground)

Distributional convergence

- **Proposition:** For all sufficiently small $\Delta > 0$, starting with any initial conditions $\theta_i(0) \in [0, T]$ for all $i \in \mathcal{N}^\star$, the temperatures of the nodes converge in distribution.

Sketch of proof

- For each possible connectivity matrix C, define a function

$$f_{\mathrm{C}} : [0,T]^n \rightarrow [0,T]^n$$

where

$$f_{\mathrm{C},i}(\Theta) = \theta_i + \Delta \left(\sum_{j=1}^{n} \lambda_{ij}^{D} \, (\theta_j - \theta_i) \, C_{ij} - (1 - C_{in}) \, \lambda_{i0} \, \theta_i \right)$$

  - Maps temperature vector Θ to another vector $f_{\mathrm{C}}(\Theta)$
    - Gives the temperature vector in the next timeslot
  - For all sufficiently small $\Delta>0$, each map is a contraction mapping

Sketch of proof …

- Starting with initial temperatures $\Theta(0)$, for all t = 0, 1, …

$$\Theta(t+1) = f_{\mathbb{C}(t)} \circ f_{\mathbb{C}(t-1)} \circ \cdots f_{\mathbb{C}(0)}(\Theta(0))$$

- Note that

$$\Theta(t+1) =_{st} f_{\mathbb{C}(0)} \circ f_{\mathbb{C}(1)} \circ \cdots f_{\mathbb{C}(t)}(\Theta(0))$$

  - Virtue of i.i.d. assumption on $\mathbb{C}(t), t = 0, 1, \ldots$

- Furthermore, $\lim_{t \to \infty} f_{\mathbb{C}(0)} \circ f_{\mathbb{C}(1)} \circ \cdots f_{\mathbb{C}(t)}(\Theta(0)) = \Theta^\star$

  exists and is independent of $\Theta(0)$

  - Consequence of contraction mappings

Conjectures

- Conjecture 1: We suspect that similar distributional convergence of temperatures holds in more general settings under necessary ergodicity assumption

- Conjecture 2: Under suitable assumptions on joint process of connectivity and temperatures (including stationarity and ergodicity) with $\mathbb{E}\left[\theta_i(0)\right] > 0$ for all $i \in \mathcal{N}^\star$, a message generated at any node will reach the sink in a finite amount of time with probability one.

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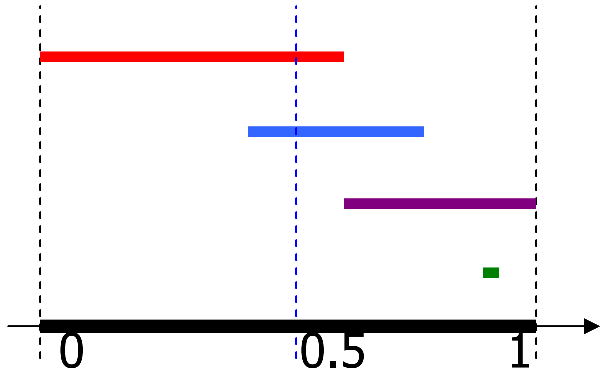
Simulation result - setup

- Four nodes moving according to Random Waypoint mobility on unit interval [0, 1]
  - Node 1 – [0.0, 0.6]
  - Node 2 – [0.4, 0.75]
  - Node 3 – [0.6, 1.0]
  - Node 4 – [0.9, 0.9]



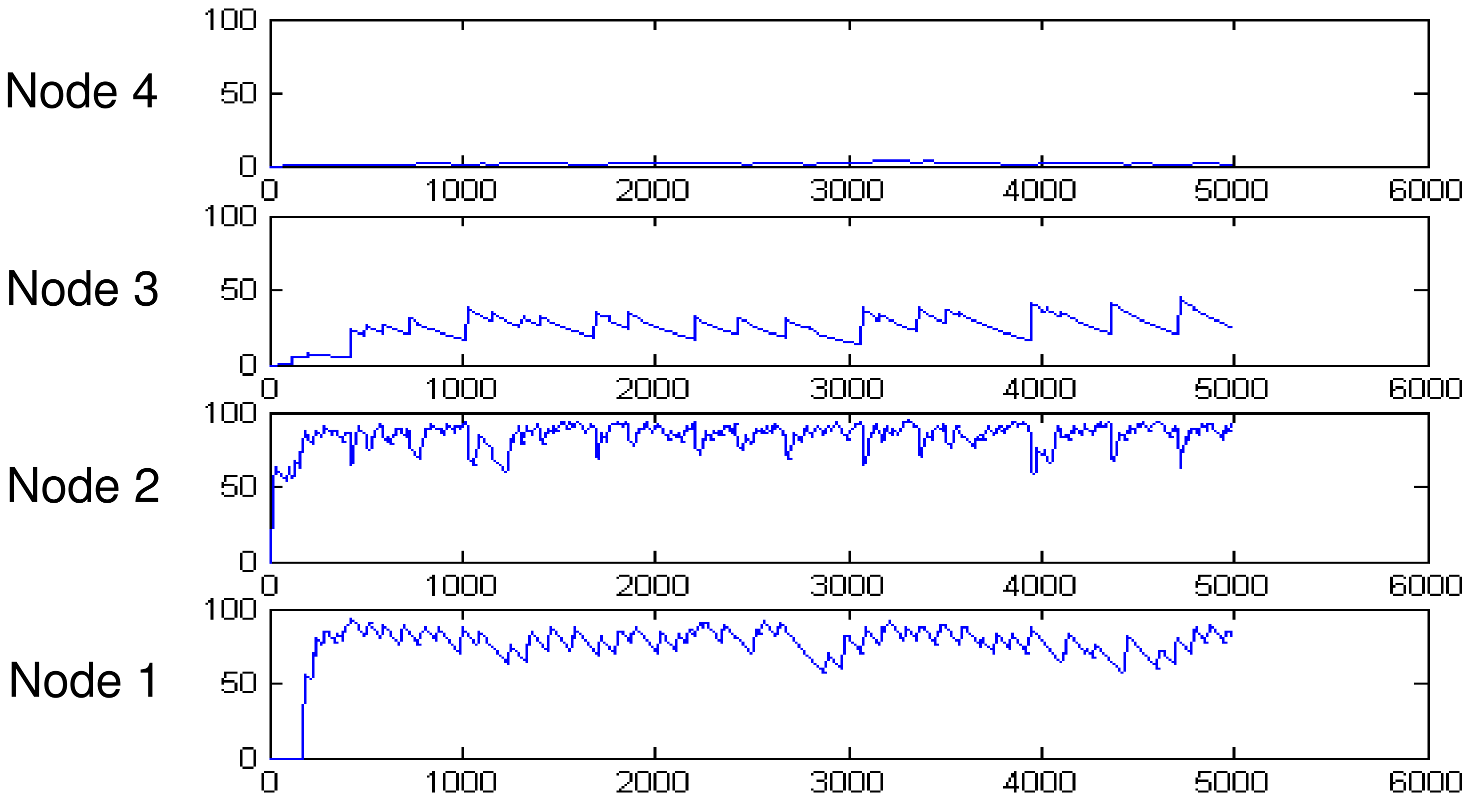
- Gateway fixed at 0.5
- Transmission range fixed at γ=0.05
- Speed range: [0.0001, 0.1]

Simulation result - setup

- Gateway temperature: $T = 100$
- Heat exchange coefficients
  - $\lambda_{i5} = 0.05,\ 1 \le i \le 4$
  - $\lambda_{ij} = 0.01,\ 1 \le i, j \le 4$
  - $\lambda_{i0} = 0.002,\ 1 \le i \le 4$
- Packets arrive according to Poisson process with rate 0.1
  - Infinite buffer size – no packet loss due to buffer overflow
- Simulation duration = 5,000

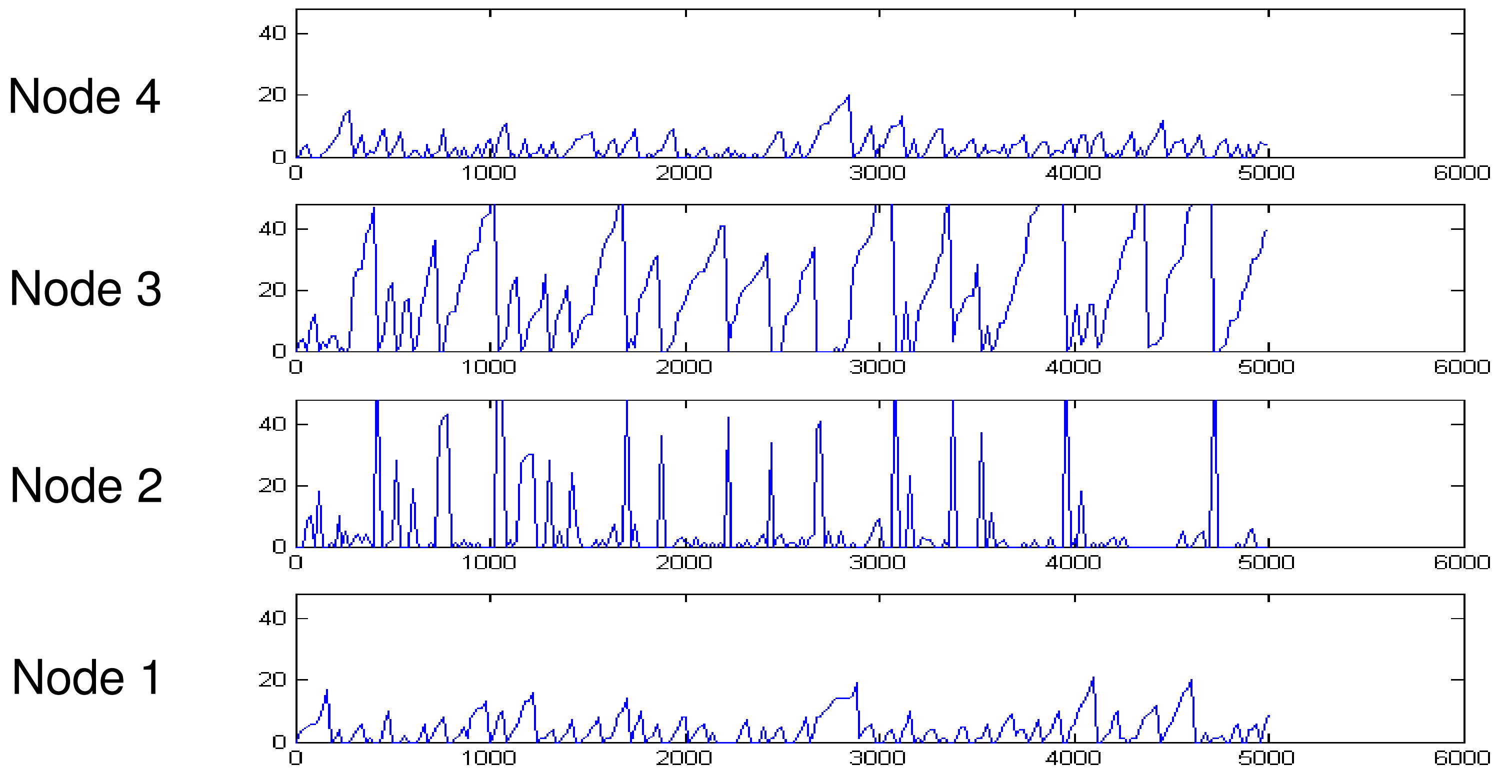
Simulation result

- Temperatures:



Simulation result

- Queue sizes:



Conclusion

- Proposed a new single-copy packet forwarding scheme
  - Inspired by thermodynamics (exchange of heat)
- Established distributional convergence
  - Discrete-time model under i.i.d. connectivity
- Suspect that similar results hold under more general settings
- Guaranteed delivery of packets within a finite delay under some conditions?